Optimal Scheduling and Control of Flexible CO_2 Capture Systems

Debangsu Bhattacharyya
Department of Chemical and Biomedical Engineering
West Virginia University, 26506

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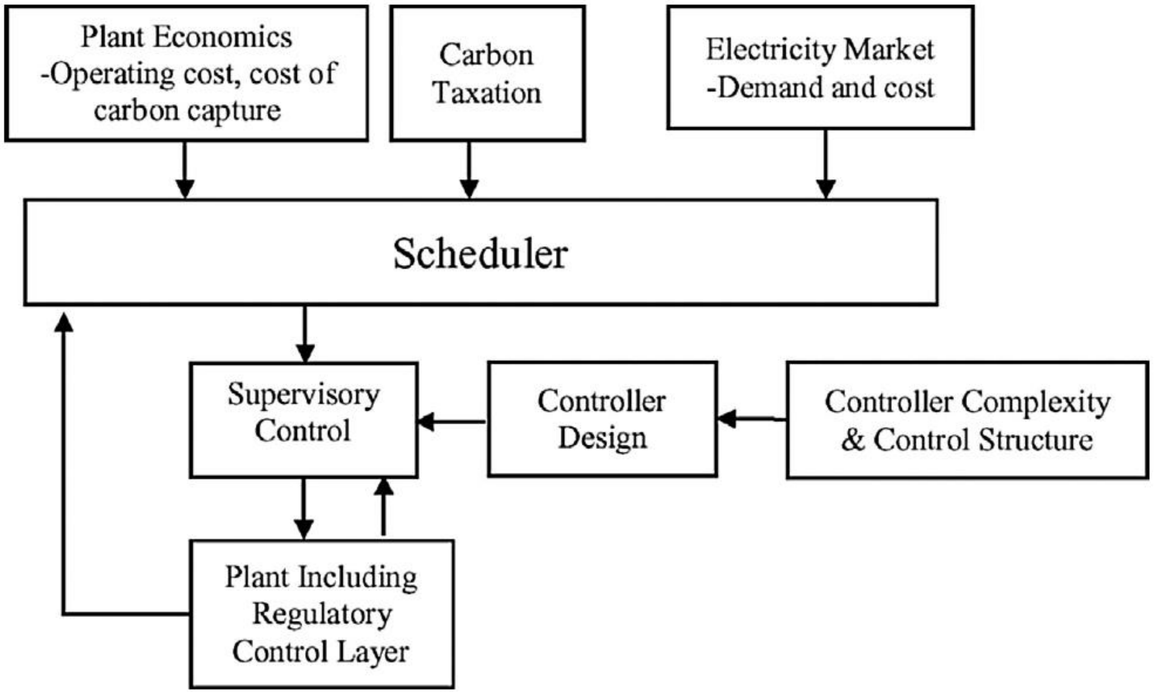
Motivation

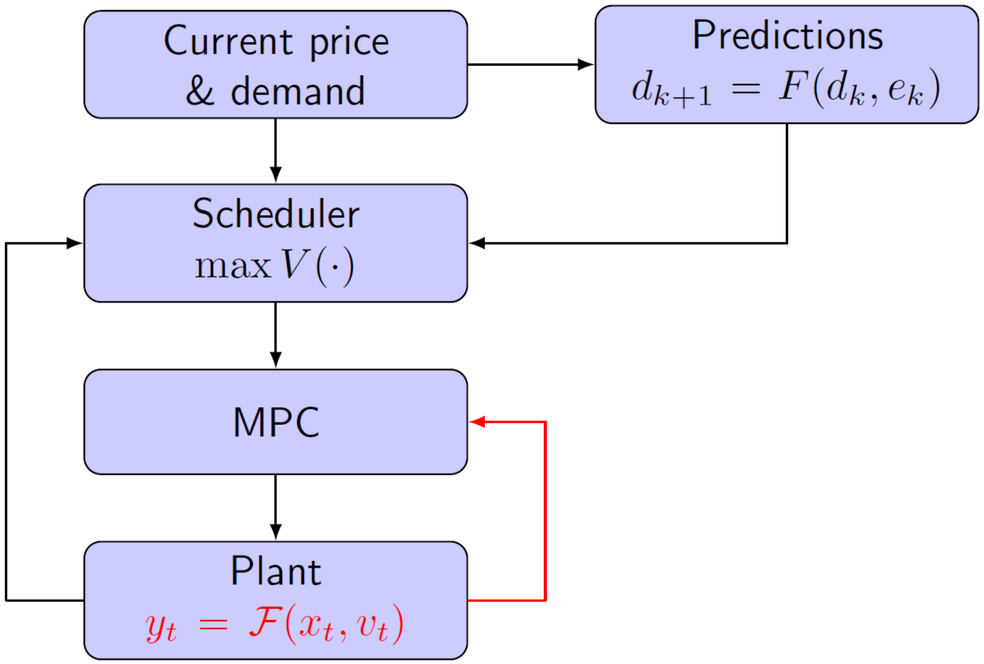
- Flexible CCS can improve the profitability of the host plant not only by capturing less CO_2 or regenerating less solvent (i.e. storing the solvent) when the electricity price and/or demand is high, but also by reducing the plant ramp rate below 'acceptable' limit for reducing the impact of load-following on emission, efficiency, and plant health.
- However the CO_2 capture targets should be satisfied within a 'base' period.
- Electricity demand and supply both are uncertain as well as the electricity price.
- Time scale for power/temperature and other variables are typically in sec/min but the 'base' period is likely to span months or years.
- Energy generation is memoryless, but the capture plant has memory due to the 'base' period.
- Optimal scheduler and controller algorithms/approaches would be critical for this multi-scale complex problem for exploiting the advantages of the flexible CCS.

Framework

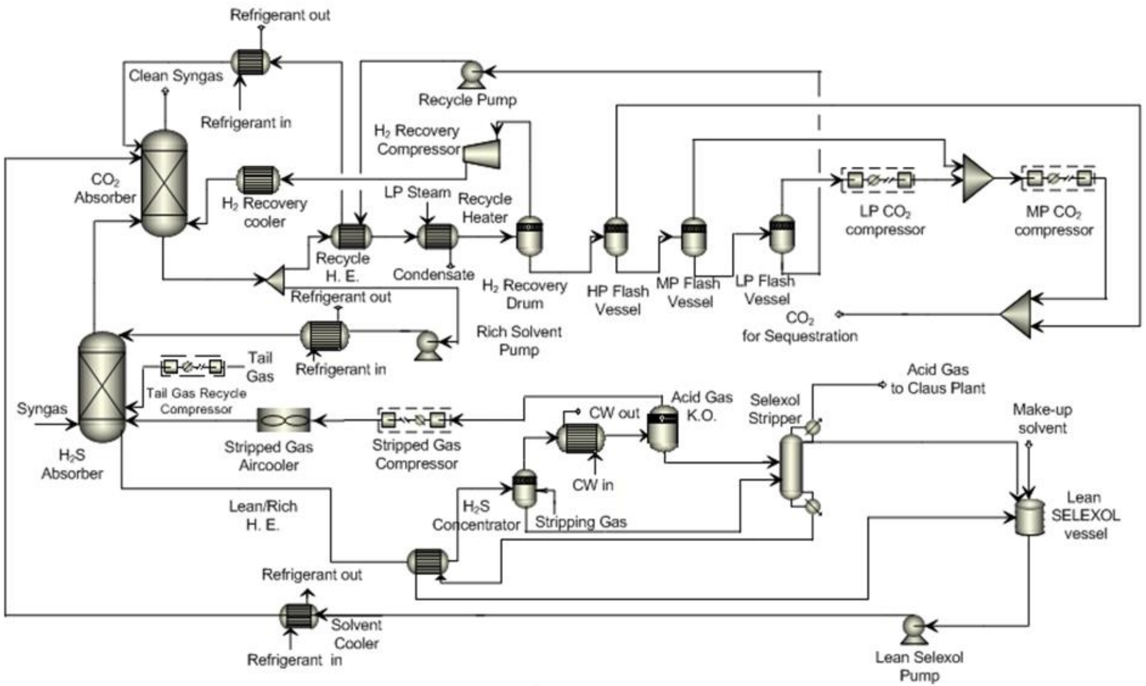


Bankole T, Jones D, Bhattacharyya D, Turton R, Zitney S, "Optimal Scheduling and its Lyapunov Stability for Advanced Load-Following Energy Plants with CO_2 Capture", Computers & Chemical Engineering, 109, 30-47, 2018

Our Approach



AGR Unit as part of an IGCC Plant



Bhattacharyya D, Turton R, Zitney S, “Steady State Simulation and Optimization of an Integrated Gasification Combined Cycle (IGCC) Plant with CO_2 Capture”, Industrial & Engineering Chemistry Research, 50, 1674-1690, 2011

Scheduler Formulation

Focus: Integrated Gasification combined cycle plant with CO_2 Capture

Revenue

OPEX

Cost of CO_2 Capture

$$\max_{u} V(d, u, \delta)$$

$$V(d,u,\delta) = \sum_{h=1}^{H} \left[\sum_{k=i+m_{h-1}+1}^{i+m_h} \left(w_{h,k} f(u_k, d_{k|i}) - p(u_k) \right) \right] - J(u, z_{cap}, \gamma, \delta)$$

subject to

$$d_{k+1} = F(d_k, e_k)$$

$$y_t = \mathcal{F}(x_t, v_t) + \omega_t$$

$$\delta = \sum_{k=1}^{i-1} y_{1,k} \left(z_{co_2} + z_{CH_4} + z_{co} - z_{cap} \right)$$

$$\Delta u_{min} \leq \Delta u \leq \Delta u_{max}$$

$$u_{min} \leq u \leq u_{max}$$

$$\boldsymbol{d} = \begin{bmatrix} \text{Electricity Demand} \\ \text{Electiricity Price} \end{bmatrix}$$

$$\boldsymbol{u} = \begin{bmatrix} \text{Electricity production rate} \\ \text{CO}_2 \text{ Capture} \end{bmatrix}$$

$$\boldsymbol{y} = \begin{bmatrix} F_{out} \\ \text{mole fraction } CO_2 \\ \text{mole fraction } CO \\ \text{mole fraction } CH_4 \end{bmatrix}$$

Various Scenarios

- **Scenario 1** :
  - Most employed form of taxation
  - All CO_2 is taxed
- **Scenario 2** :
  - CO_2 is taxed beyond an acceptable limit
  - e.g., Alberta: $15/ton beyond 100,000 ton annual emission
- **Scenario 3** :
  - Cap and trade
  - CO_2 credits can be traded

Carbon capture constraint is applicable during the base time

Cost of CO_2 Capture

- Scenario 1

$$J = \gamma \cdot \sum_h \left(\sum_k F_k \left(\bar{z}_{co_2} + \bar{z}_{CH_4} + \bar{z}_{co} - z_{cap} \right) \right)$$

- Scenario 2

Cumulative Past deviation

Expected future deviation

$$\epsilon = \sum_{k=1}^{t-1} F_{out} \cdot \left(z_{co_2} + z_{CH_4} + z_{co} - z_{cap} \right) +$$

$$\sum_h \left(\sum_k F_k \left(z_{co_2} + z_{CH_4} + z_{co} - z_{cap} \right) \right)$$

$$J = \begin{cases} \gamma \cdot \epsilon & \epsilon \geq 0 \\ 0 & \epsilon < 0 \end{cases}$$

Cost of CO_2 Capture

- Scenario 3

Cumulative Past deviation

Expected future deviation

$$\epsilon = \sum_{k=1}^{i-1} F_k \cdot (z_{co_2} + z_{CH_4} + z_{co} - z_{cap}) + \sum_{h} \left(\sum_{k} F_k \, (z_{co_2} + z_{CH_4} + z_{co} - z_{cap}) \right)$$

$$J = \begin{cases} \gamma_{\text{buy}} \cdot \epsilon & \epsilon \geq 0 \\ -\gamma_{\text{sell}} \cdot \epsilon & \epsilon < 0 \end{cases}$$

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Design of the Supervisory Control Layer

Optimal Selection of the Number of Centralized Controllers using Gramian-Based Interaction Measures:

$$P = \int_0^\infty e^{A\tau} B B^T e^{A^T \tau} d\tau \qquad Q = \int_0^\infty e^{A\tau} C C^T e^{A^T \tau} d\tau$$

Participation Matrices (PM): $[\Phi]_{ij} = \dfrac{tr(P_j Q_i)}{tr(PQ)}$

$$\|G\|_H = \sqrt{\lambda_{\max}(G)}$$

Hankel Interaction Index Array (HIIA): $[\Sigma_H]_{ij} = \dfrac{\|P_i Q_j\|_H}{\sum_{kl} \|P_k Q_l\|_2}$

$$\|G(s)\|_2 \equiv \sqrt{\sum_{i,j} \int_0^\infty |g_{ij}(\tau)|^2 d\tau}$$

Σ_2 Measure: $[\Sigma_2]_{ij} = \dfrac{\|P_j Q_i\|_2}{\sum_{kl} \|P_k Q_l\|_2}$

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Controller Complexity and MPC Tuning

A measure of the computational time for the centralized controllers:

$$\mathcal{O}(n^2 ln(n)\ )$$

$$\min_{v,y} \ \left(J_{control}\ (v,\mathrm{y}) \cdot (v+\mathrm{y})^2 ln(v+\mathrm{y})\right)$$

Optimal output and move suppression weights:

$$\min_{\Psi,\Phi} \sum_{i=1}^{n_y} \Theta_i ISE_{\mathbf{y}_i}$$

s.t.

$$\Gamma(r,y,v,t) \leq 0$$

Lyapunov Stability

$$\max_{u} V(d, u, \delta) = \sum_{k} l(d_k, u_k, y_k, \delta_k)$$

subject to

$$d_{k+1} = F(d_k, e_k)$$

$$y_t = \mathcal{F}(x_t, v_t) + \omega_t$$

$$\delta = \sum_{k=1}^{i-1} y_{1,k} \left(z_{co_2} + z_{CH_4} + z_{co} - z_{cap} \right)$$

$$\bar{d}_k = d_k - d_k^*$$

$$\bar{u}_k = u_k - u_k^*$$

$$\bar{y}_k = y_k - y_k^*$$

$$\bar{\delta}_k = \delta_k - \delta_k^*$$

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Lyapunov Stability

Definition:

A κ_∞ function is a continuous single valued function $\Phi : [0, \infty) \rightarrow [0, \infty)$:

- it is stricly increasing
- $\lim_{r \rightarrow \infty} \kappa_\infty(r) = \infty$

Assumptions:

- Underlying process is controllable $\implies \forall\, x(0) = x_0 \;\exists\; t > 0 : x(t) = x_f(t)$
- $\bar{F}(\bar{d}_k), \bar{l}(\bar{d}, \bar{u}, \bar{y}, \bar{\delta})$ are both Lipschitz continuous :
  $|F(\bar{d}_1) - F(\bar{d}_2)| \leq l_f |\bar{d}_1 - \bar{d}_2|,$
  $|l(\bar{d}_1, \bar{u}_1, \bar{y}_1, \bar{\delta}_1) - l(\bar{d}_2, \bar{u}_2, \bar{y}_2, \bar{\delta}_2)| \leq l_l |(\bar{d}_1, \bar{u}_1, \bar{y}_1, \bar{\delta}_1) - (\bar{d}_2, \bar{u}_2, \bar{y}_2, \bar{\delta}_2)|$
- $\bar{l}(\bar{d}, \bar{u}, \bar{y}, \bar{\delta}) \geq \Psi(|\bar{d} - 0|)$ where $\Psi(\cdot) = \kappa_\infty$

Lyapunov Stability

Additional assumptions:

The optimization problem satisfies the linear independent constraint qualification, sufficient second order conditions and strict complementarity at the solution.

Lemma:

The stability of the transformed system with stage cost $\bar{l}(\bar{d},\bar{u},\bar{y},\bar{\delta})$ at $(0,0,0,0)$ is equivalent to the stability of the original system with stage cost $l(d,u,y,\delta)$ at (d^*,u^*,y^*,δ^*).

Lemma:

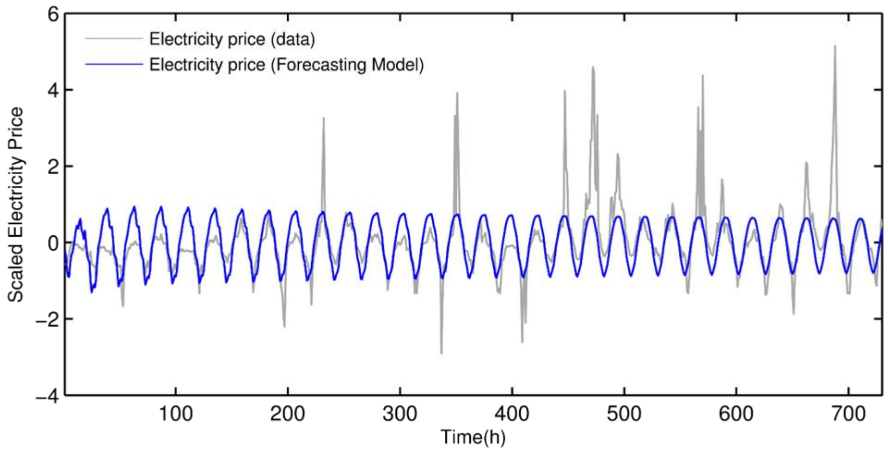
Based on the assumptions given before, then $V(i)$ as defined earlier is a Lyapunov function and the transformed system is asymptotically stable at $(0,0,0,0)$.

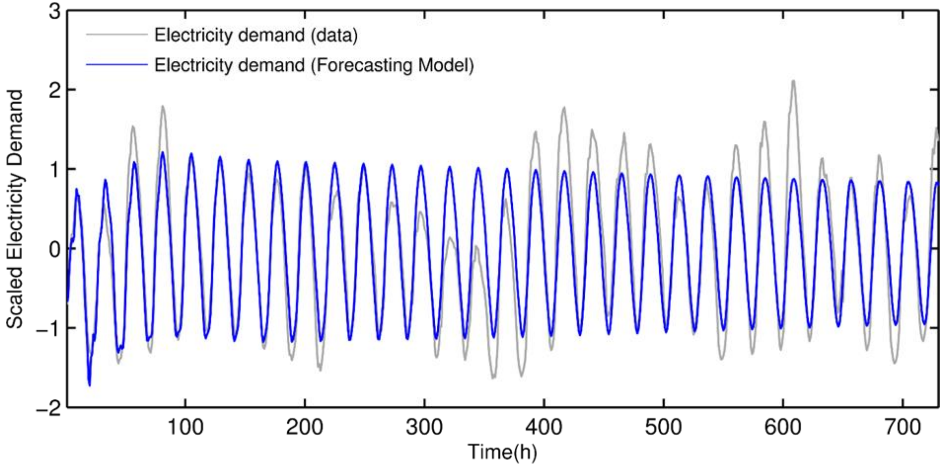
Forecasting Model

Stochastic Forecasting Model :

$$q_{k+1} = \bar{A}q_k + \bar{B}e_k$$

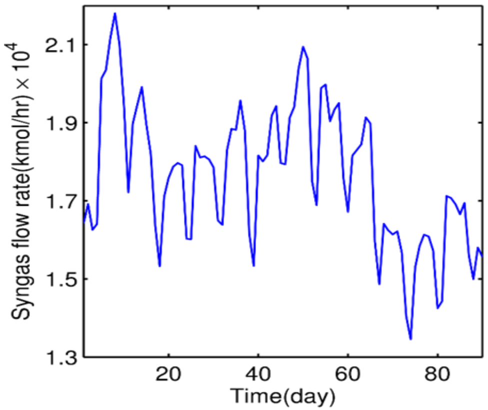
$$d_{k+1} = \bar{C}q_k$$

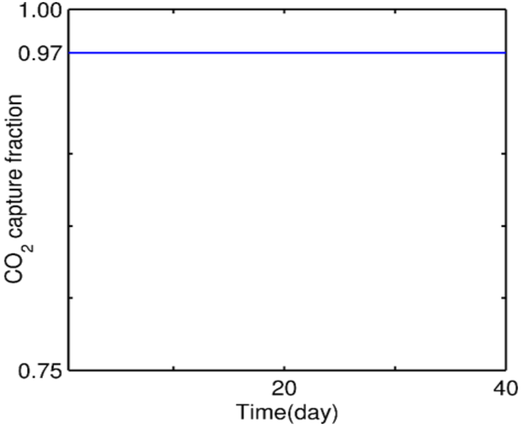


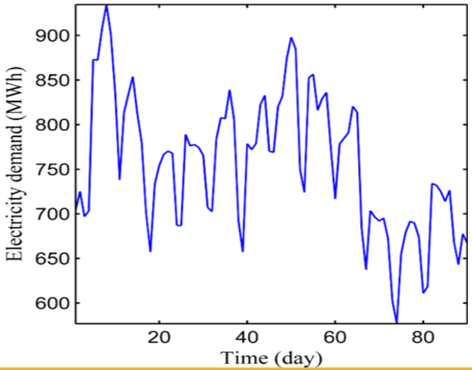


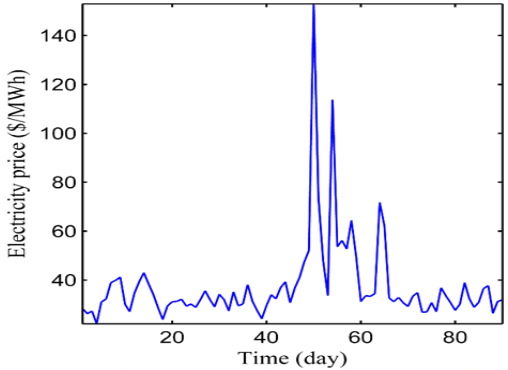
Results

Scenario 1:



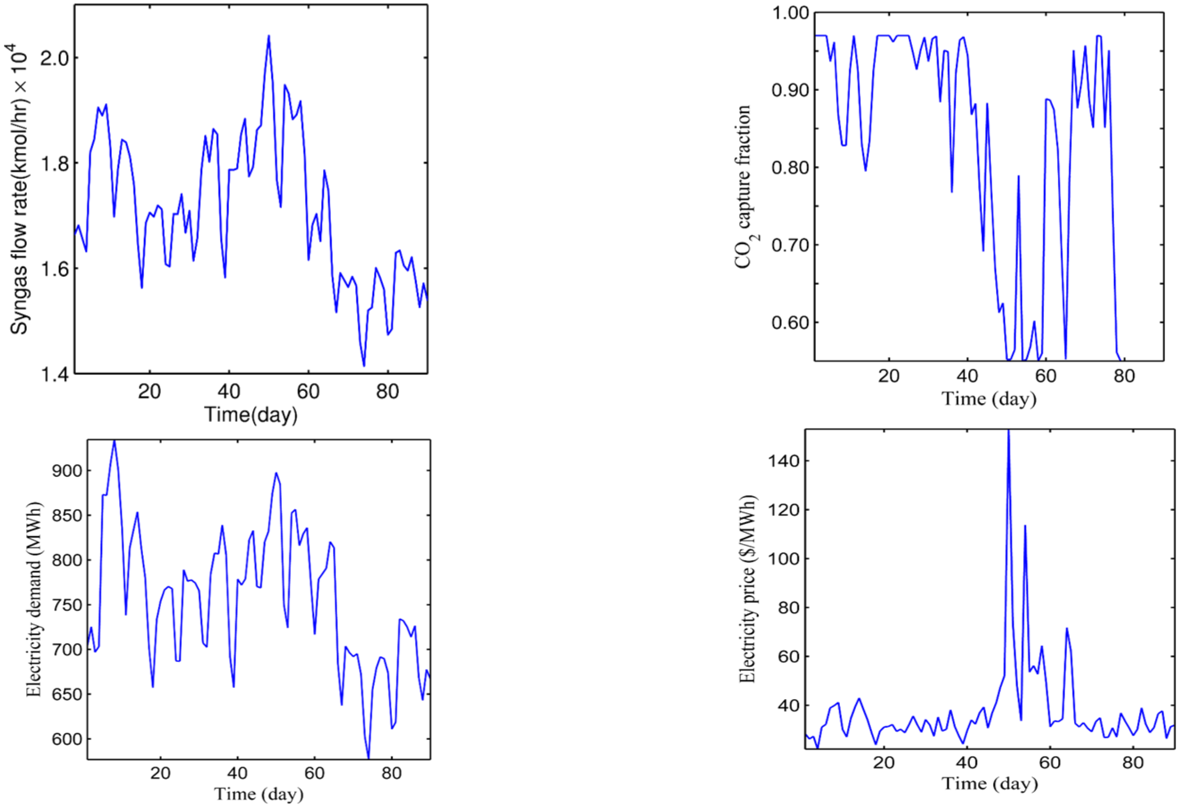






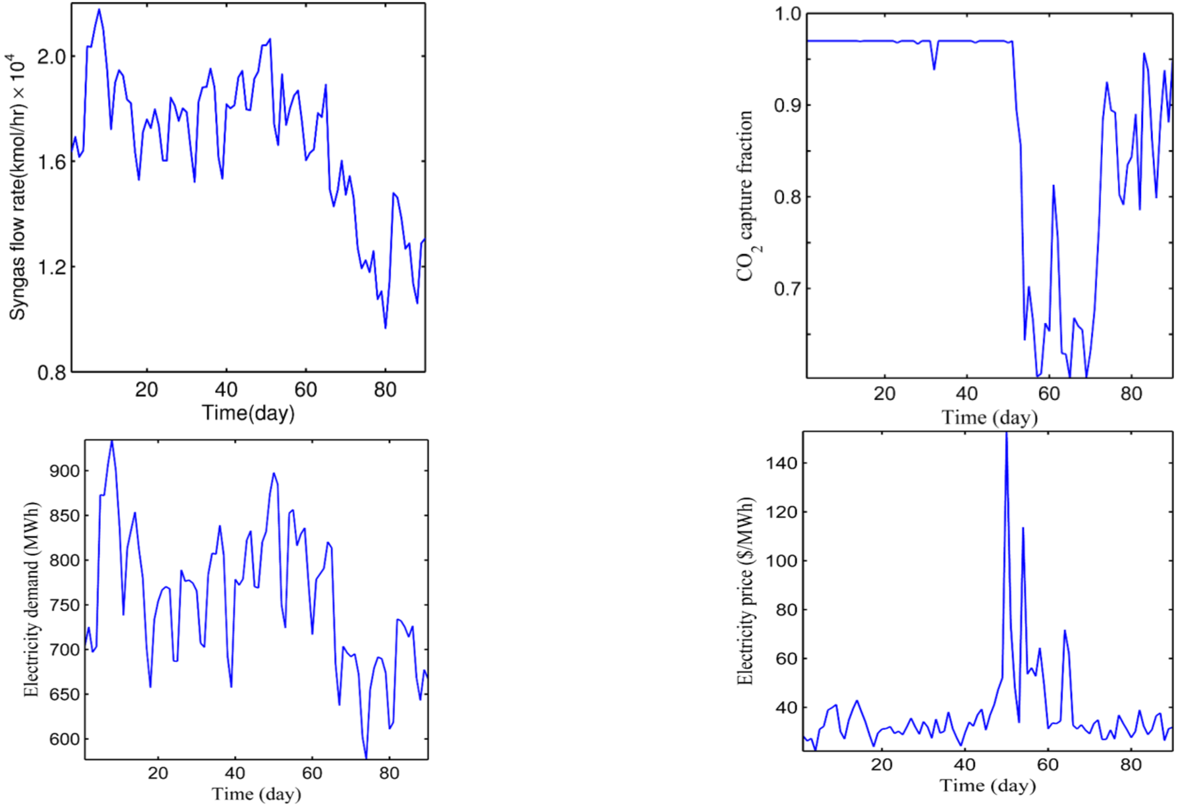
Results

Scenario 2:



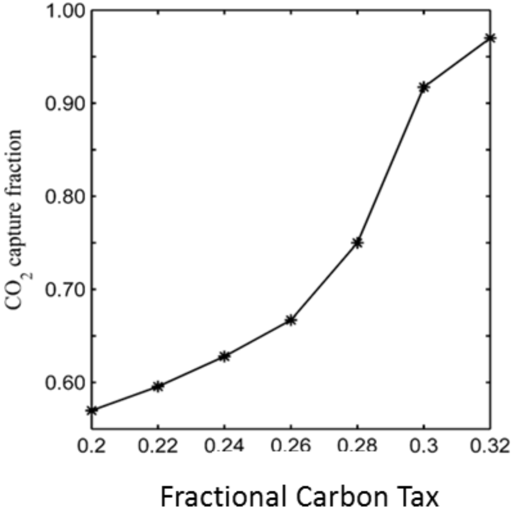
Results

Scenario 3:

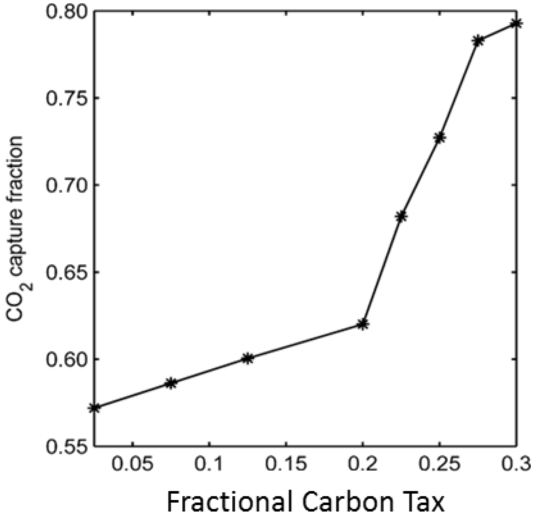


Impact of Carbon Tax

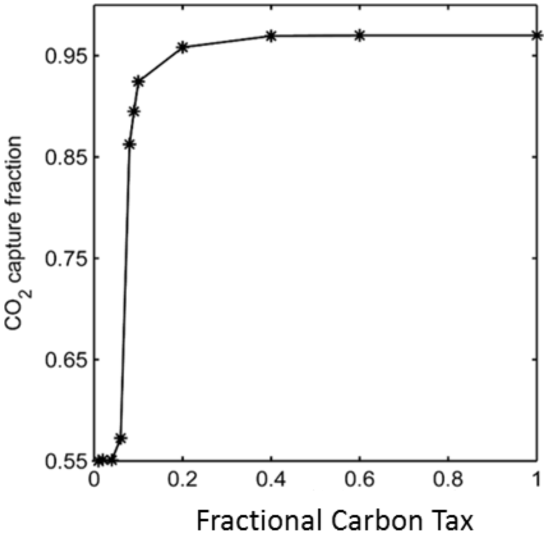
Scenario 1:



Scenario 2:



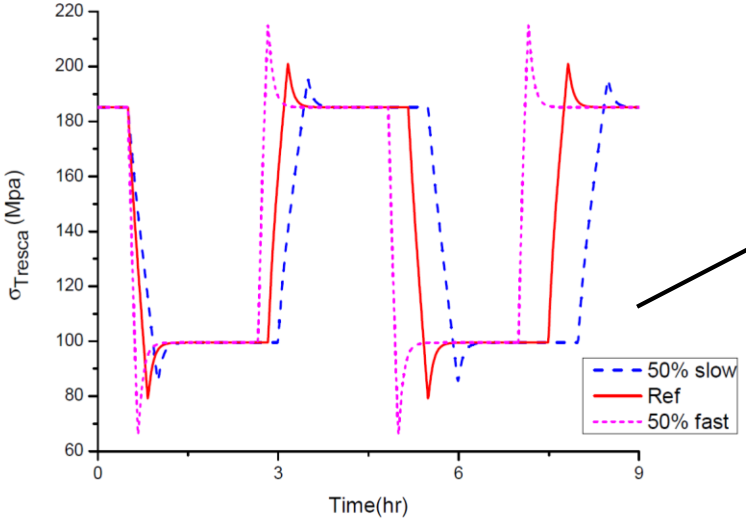
Scenario 3:

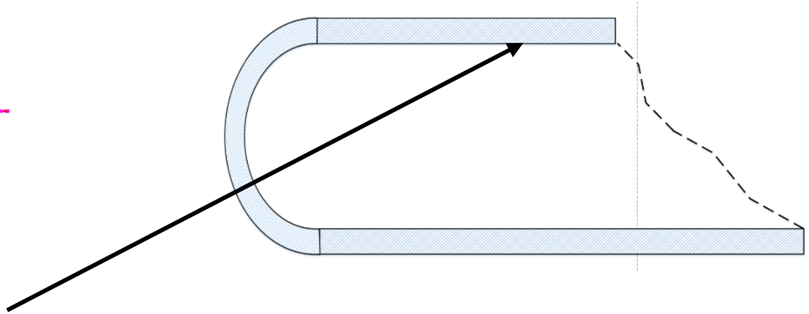


Future Thoughts

- Flexible CCS taking into consideration the health impact of load-following (health modeling is an ongoing work as part of IDAES and another DOE project).

Drum material: SA 302B

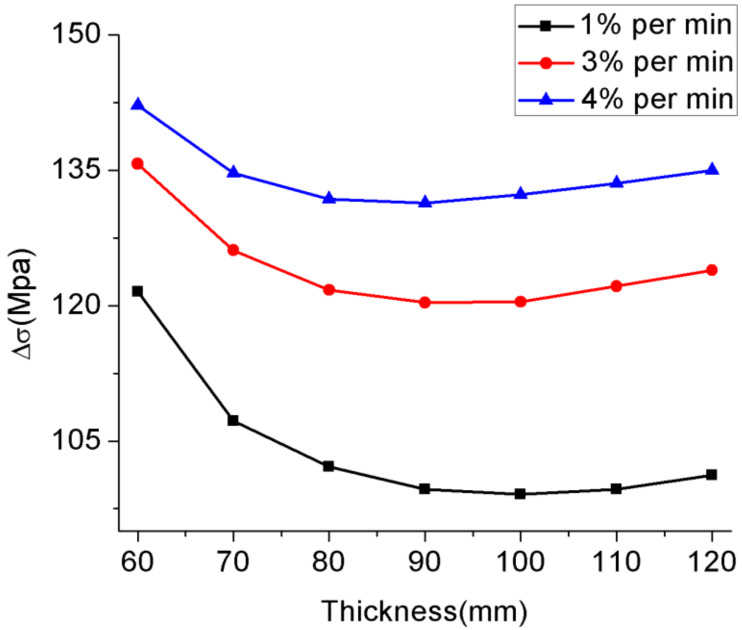


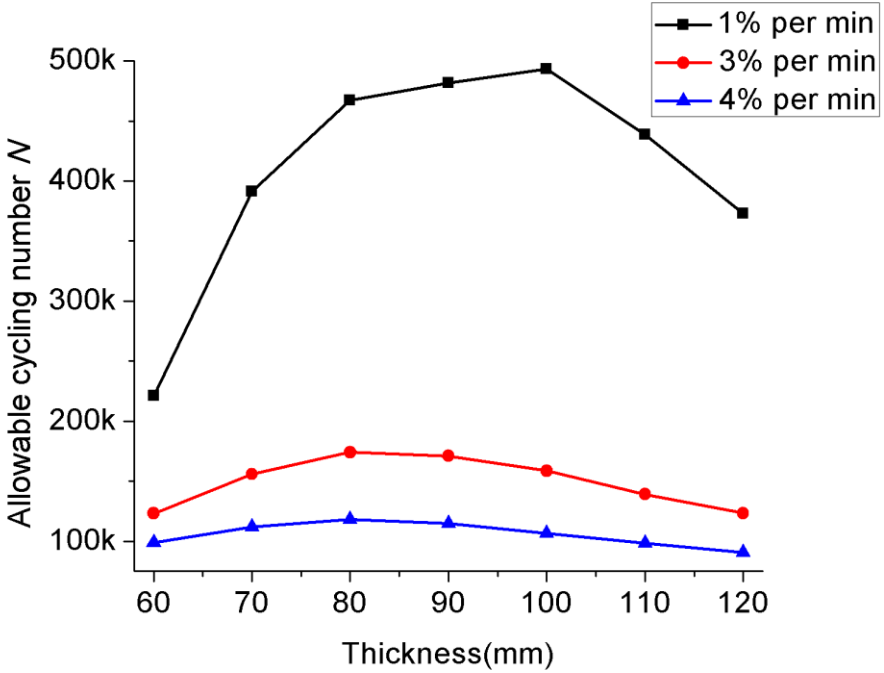


	50% Slower	Ref Rate*	50% Faster
*N***(Times)	600,000	350,000	140,000

*** Results obtained using EN 13345 Part 3**

Future Thoughts





Based on German code TRD 301

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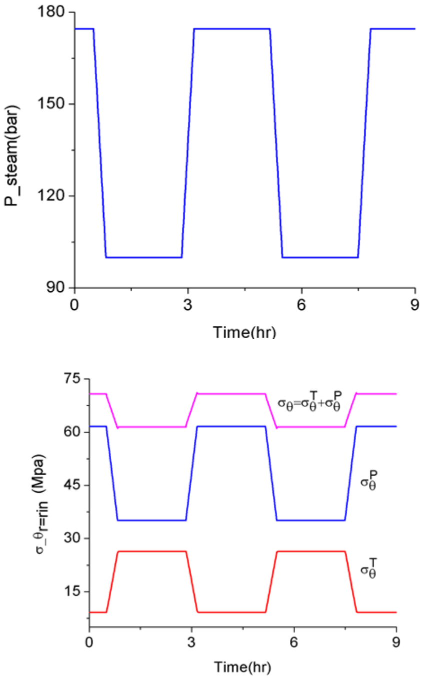
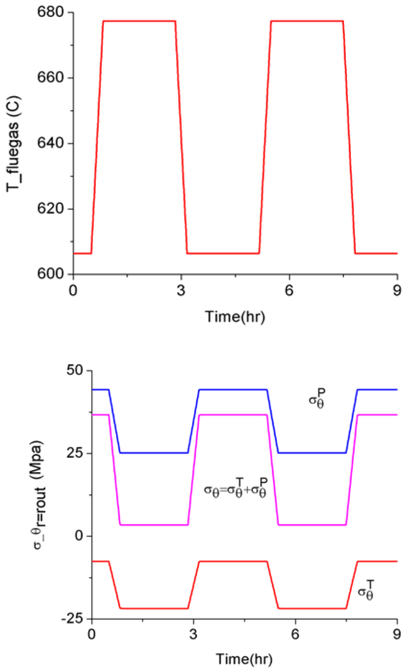
Future Thoughts

Impact of creep and fatigue on superheater/reheater tube failure:



Tube Inner Surface



Tube Outer Surface

- **Impact of Creep** (austenitic steel):
  - Inner surface temperature: 650^{o}C, σ_{eff} =176 MPa, Estimated rupture time: 80,000 hr,
  - Inner surface temperature: 600^{o}C, σ_{eff} =66 MPa, Estimated rupture time: 7 x 10^{6} hr
- **Impact of Fatigue** (3% ramp change per minute):
  - Allowable cycle number: 35,000.

* Results obtained using EN 13345

Future Thoughts

- When plant health is taken into consideration, the ‘end period’ becomes time-varying and stochastic. In addition, the health model has ‘memory’. For general class of nonlinear systems, it leads to a challenging scheduling and control problem.
- Short-term gain vs long-term loss needs to be weighed with due consideration of risk, probability of failure, O&M cost, and future energy outlook.
- Stability of the scheduling and control problem needs to be investigated by characterizing and quantifying the uncertainty.
- Algorithms for this multi-scale problem need to be formulated with due consideration of computational cost and robustness for deployment in real-life scenarios.

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Thank You